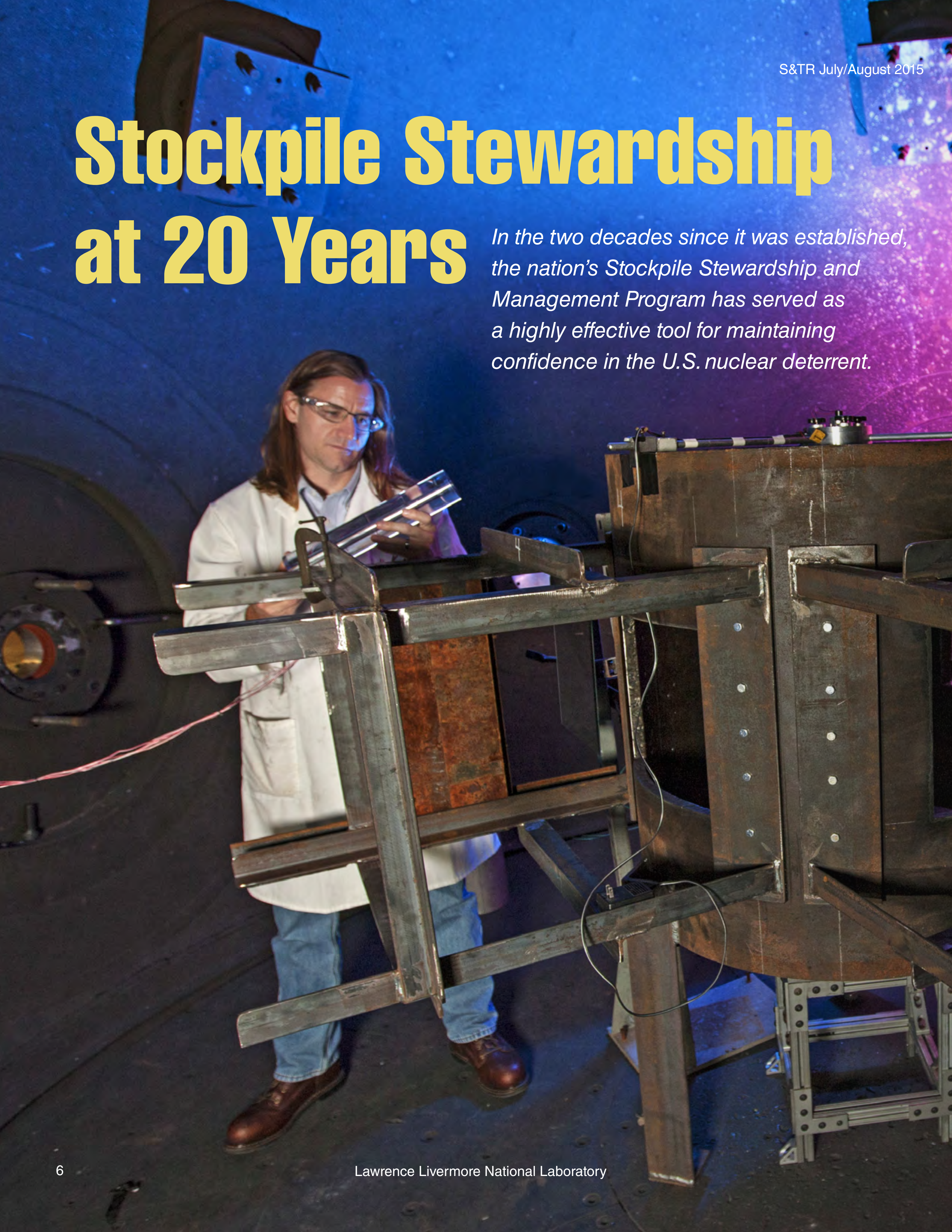
Stockpile Stewardship at 20 Years

In the two decades since it was established, the nation's Stockpile Stewardship and Management Program has served as a highly effective tool for maintaining confidence in the U.S. nuclear deterrent.



FOLLOWING the collapse of the Soviet Union and the end of the Cold War, the United States took a series of bold steps to strengthen nuclear nonproliferation. These steps included halting underground nuclear testing, ceasing the development of new nuclear weapons, reducing the size of the existing nuclear stockpile, and beginning to close nonessential elements of the nuclear weapons production complex. In September 1996, President Clinton formally announced his decision to seek a Comprehensive Nuclear-Test-Ban Treaty (CTBT) and directed the Department of Energy (DOE) to take the required actions for sustaining confidence in the stockpile without nuclear testing. Thus, the Stockpile Stewardship and Management Program was formally established to maintain the safety, security, and reliability of the U.S. nuclear deterrent without full-scale testing.

Details of the program were arrived at following months of close consultation between the directors of the three DOE weapons laboratories (Livermore, Los Alamos, and Sandia national laboratories), DOE officials, and congressional leaders. The new approach relied on advanced scientific understanding through a combination of theoretical advances, nonnuclear (including subcritical) experiments, supercomputer simulations, and enhanced stockpile surveillance—not on additional nuclear testing—to predict, identify, and correct stockpile problems.

A key architect of the fledgling program, DOE's Assistant Secretary for Defense Programs Vic Reis, addressed Livermore employees in October 1995 to discuss the ambitious effort. Reis told employees the "awesome responsibility" for decisions regarding the safety and reliability of the nation's nuclear weapons stockpile "has been put right back where it belongs—with the labs."

The new program posed significant challenges for the DOE weapons laboratories. Weapons typically were

(left) Kevin Vandersall, a researcher in Livermore's High Explosives Applications Facility (HEAF), inspects equipment and diagnostics prior to an energetic materials experiment. HEAF is home to some of the best-equipped high-explosives research and testing laboratories in the world. (Photograph by George A. Kitrinos.) (right) The Laboratory conducted many highly complex underground nuclear tests at the Nevada Test Site (now the Nevada National Security Site) prior to the commencement of the Stockpile Stewardship and Management Program.

designed for a 20-year service life and most often were replaced before then with newer designs. For more than four decades, nuclear testing had provided the means to assure confidence in the stockpile. Bruce Goodwin, associate-director-at-large for Global Security Research, described the challenge as analogous to maintaining a 40-year-old car. "New parts cannot be obtained, and in some cases you can't make replacement parts because they require materials that are environmentally prohibited or are no longer available," he says. "You have to ensure that the car runs, but you're not allowed to start it." Nevertheless, "it has to work with 100 percent reliability."

The weapons laboratories now had to understand in far greater detail how materials' aging processes might affect weapons performance years into the future and to use this information for anticipating when serious issues might initially arise. To succeed in the radically reworked assignment, weapons scientists and engineers required more advanced nonnuclear experimental capabilities. Toward this end, the National Ignition Facility (NIF) was built at Lawrence Livermore, and some of the Laboratory's other facilities, such as the Contained Firing Facility (CFF) at Site 300 and and the High Explosives Applications Facility (HEAF), were significantly upgraded. A series of progressively more powerful supercomputers was also acquired. These computational machines integrated existing nuclear test data and increasing amounts of scientific data on stockpile materials' performance and aging characteristics. They also served as a surrogate test platform using far more accurate predictive models.

Charlie Verdon, principal associate director for the Weapons and Complex Integration (WCI) Principal Directorate, notes that stockpile stewardship has enabled the three directors of the DOE weapons laboratories—now DOE National Nuclear Security Administration (NNSA) national security laboratories—to provide the U.S. president an annual assessment of the safety and reliability of the stockpile for more than two decades with no identified need for an underground nuclear test. Verdon says, "This work is a remarkable achievement given the major shift in methods and the many uncertainties at the start of the program." He notes, however, that the program faces continuing challenges as weapons age.

Enhanced Surveillance

A central focus of the Stockpile Stewardship and Management Program was to enhance routine surveillance of weapons with a combination of predictive aging models and nondestructive testing to forecast and detect age-related material changes at an early stage. For example, plastics break down, metals corrode, and coatings deteriorate in response to long-term exposure to radiation, fluctuating temperatures, and other environmental conditions. Advanced computational models show how materials outgas; polymers slowly change their chemistry; gas bubbles form, grow, and diffuse; explosives recrystallize and interact with binders; materials interact with atmospheric gases, such as water vapor, hydrogen, and oxygen; and how long-term radiation exposure changes materials. (See the article beginning on p. 22.)

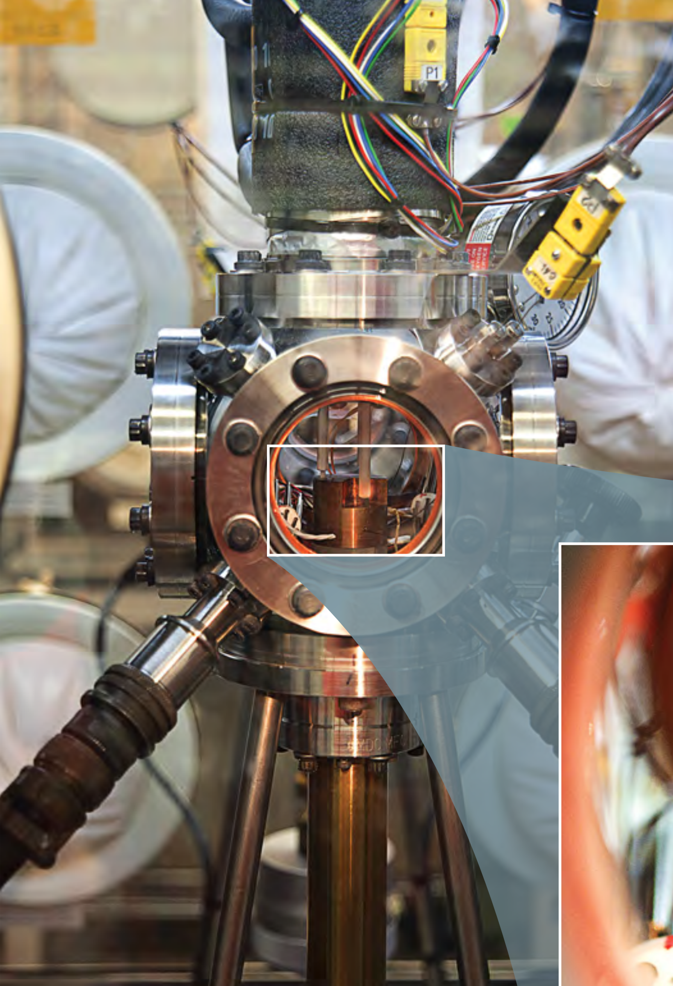
Physical chemist Bill McLean, enhanced surveillance campaign manager, says, "With a shrinking stockpile, disassembling and discarding assets to find potential problems is not always practical." Stockpile stewardship has enabled the development of new nondestructive surveillance technologies to identify potential safety or reliability problems such as corrosion, cracks, and compositional changes without the need for destructive dismantlement.

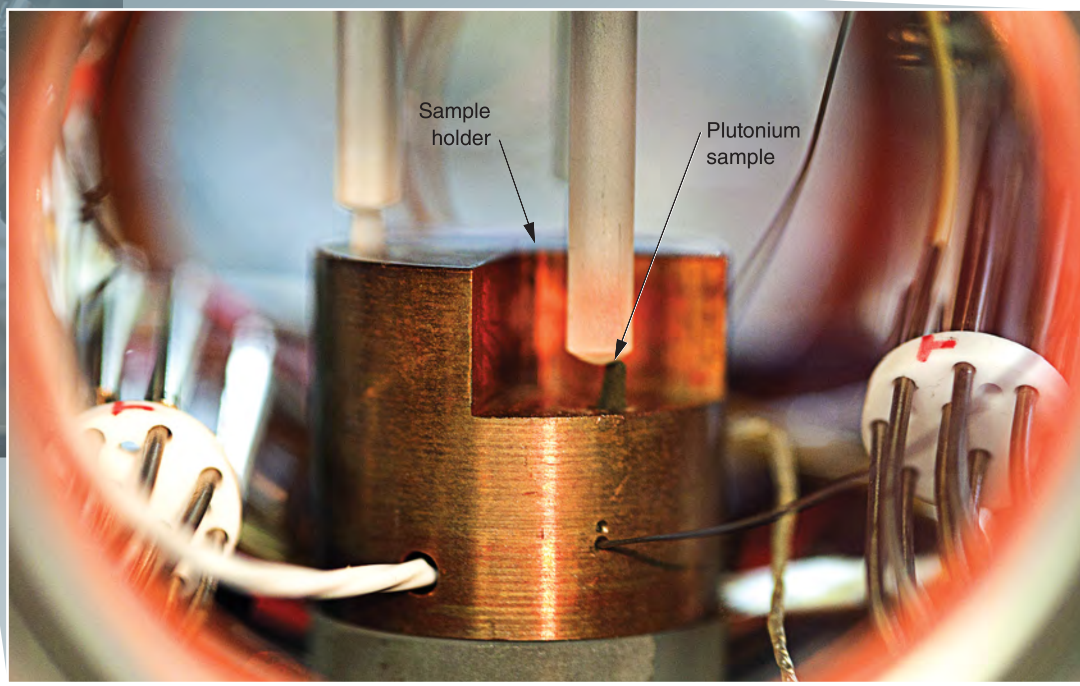
One important surveillance tool, called CoLOSSIS (Confined Large Optical Scintillator Screen and Imaging System), is an x-ray computed tomography system to detect aging defects on critical components in nuclear weapons. Developed by Livermore scientists and located at NNSA's Pantex Plant in Texas, this high-resolution imaging system assembles two-dimensional (2D) digital radiographs into a three-dimensional (3D) tomographic image that scientists analyze to discover any anomalies. Since its installation in 2009, the rate and quality of surveillance efforts have increased dramatically. Researchers are continuing to develop more efficient scintillators for converting x rays to light and to increase the speed of tomographic image reconstruction.

As a complement to existing x-ray diagnostic tools such as CoLOSSIS, Livermore researchers are building a prototype high-energy (10-megaelectronvolt) neutron imaging facility. The machine, scheduled for completion in 2019, is designed to detect cubic-millimeter-scale voids, cracks, and other defects in heavily shielded or low-Z materials such as plastics and polymers. It will be capable of producing 2D radiographic and 3D tomographic images.

Plutonium Aging Gracefully

Since the end of nuclear testing, scientists have been particularly concerned about how plutonium ages because unexpected changes in the element's chemical structure (or phase) could compromise weapons performance. In particular, scientists worried about the damage accumulated over decades as plutonium-239 decays and self-irradiates. In response, Livermore scientists launched experiments at the Laboratory's Superblock, a city-block-long assemblage of actinide research facilities. (Complementary efforts were conducted at Los Alamos National Laboratory.) The ongoing experiments involve samples of plutonium-239 taken from old weapons and from plutonium-239 artificially aged to 200 equivalent years at present. The tests showed no significant changes in pertinent physical properties





Samples of naturally and artificially aged plutonium, each 2 or 3 centimeters long, are measured in dilatometry experiments to check for changes in the samples' volumes over time.

such as density and strength. As a result, scientists determined the minimum lifetime for plutonium in existing weapons is at least 85 years. (See *S&TR*, December 2012, pp. 11–14.)

Chemist Pat Allen, the enhanced surveillance deputy program leader who also leads plutonium aging studies, notes that Livermore researchers have gained a tremendous amount of knowledge about the aging mechanisms of both uranium and plutonium as well as their static properties. However, "We have to better understand the behavior of plutonium under dynamic conditions, which is a real challenge," says Allen. He points to a recent series of plutonium experiments at NIF conducted under a regime of extreme pressures and temperatures that are beginning to yield significant new data.

Dynamic plutonium experiments also continue at two facilities located at the Nevada National Security Site. At the underground U1a complex, chemical high explosives (HEs) are detonated next to samples of plutonium-239 to obtain data on its dynamic behavior. These tests are called subcritical experiments because the configuration and quantities of explosives and special nuclear materials such as plutonium cannot create a self-sustaining nuclear chain reaction, or criticality. Subcritical experiments are thus consistent with the U.S. nuclear testing moratorium and CTBT.

Underground U1a experiments complement those conducted at the Joint Actinide Shock Physics Experimental Research (JASPER) Facility. JASPER captures data on the properties of plutonium at high shock pressures and temperatures close to those experienced in nuclear weapons. JASPER experiments use projectiles moving at 8 kilometers per second to impact plutonium targets fabricated at the Superblock.

"We're just beginning to understand dynamic behavior," says Allen. The new studies are part of what he terms "Stockpile Stewardship 2.0," an effort dedicated to understanding the dynamic behavior of both nuclear and nonnuclear materials, including those produced through new manufacturing techniques such as additive manufacturing. NIF experiments are expected to play a large role in this effort.

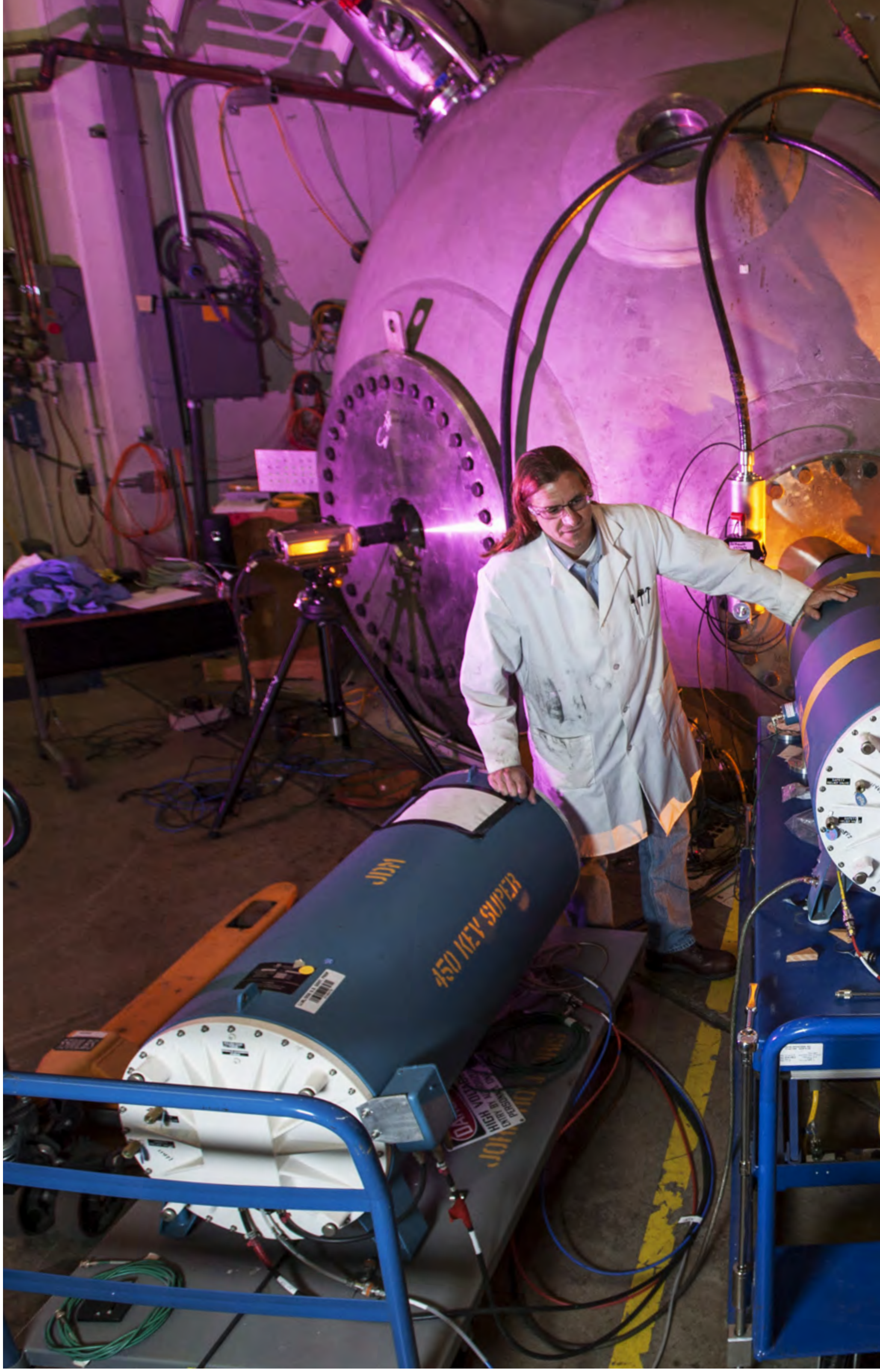
Long-Lasting High Explosives

One of stockpile stewardship's most important advances has been increased understanding of HEs. Composed of HE powder and inert plastic binder, HEs are used in the main charge, booster, and detonator of a nuclear weapon's firing system. Jon Maienschein, director of Livermore's Energetic Materials Center, says, "We have to understand how high explosives change over time and how these changes might affect future stockpile functionality." He notes, however, that Livermore formulations have proven themselves extremely stable. "We expect our HEs to be long-lasting because we designed them that way," he says, adding that surveillance activities are validating this expectation.

High-fidelity simulations mimic the extremely rapid physical and chemical detonation processes of energetic materials. They reflect accurate physical models that are used to predict likely changes in weapons' HEs during the next one to two decades. HE computational models also allow scientists to assess data from HE and hydrodynamic tests and precisely reproduce these experiments.

"From a scientific perspective stockpile stewardship has been beneficial for developing a much deeper scientific understanding of all materials," says Maienschein. "We've progressed from observing high explosives being blown up to carefully studying their chemistry, morphology, crystallinity, and aging characteristics."

HEAF is home to some of the best-equipped HE research and testing laboratories in the world. Researchers at the facility conduct all aspects of explosives research, from synthesizing new materials to characterizing their safety and detonation properties. In 2008, NNSA named Lawrence Livermore its High Explosives R&D Center of Excellence.



Working in HEAF laboratories, Livermore chemists have developed "insensitive" HEs that are much less likely to accidentally detonate than the already safe conventional HEs used in most weapons. Insensitive HEs are remarkably impervious to heat, shock, and impact, including from small arms fire. A new Livermore HE formulation, LX-21, is based on the Laboratory-developed HE molecule LLM-105, and has proven notably insensitive in advanced testing.

HEAF research complements experiments at CFF involving up to 60 kilograms of HE. The world's largest indoor firing facility, CFF capabilities include high-resolution imaging and velocity measurements of detonating

Researchers Kevin Vandersall and Joe Tringe prepare to conduct an explosives test in one of HEAF's seven indoor firing tanks. (Photograph by George A. Kitrinos.)

nonnuclear weapons assemblies. These hydrodynamic tests create temperatures and pressures so great that solids behave like liquids. CFF's sister facility, the Dual- Axis Radiographic Hydrodynamic Test (DARHT) Facility, is located at Los Alamos National Laboratory. It uses two large x-ray machines instead of one to record interior images of materials and fashion them into ultrafast motion pictures of the detonation. CFF and DARHT offer complementary capabilities and are jointly used by Livermore and Los Alamos for conducting hydrotests.

Extending Weapons' Lives

A vital element of stockpile stewardship, life-extension programs (LEPs) address weapons issues discovered through routine surveillance and annual stockpile assessments, such as aging effects that could lead to future performance degradation. Depending on the nature of these changes, parts may need to be replaced or refurbished to meet safety, security, and reliability requirements. In this way, LEPs can extend the weapons' lifetimes for an additional 20 to 30 years without the need to conduct underground nuclear tests.

NNSA national security laboratories design the parts required for LEPs and certify the life-extended weapons when they enter the stockpile. Currently, Livermore has been assigned an LEP for the W78/88-1, a system to be interoperable between Air Force and Navy missile systems. However, the effort is currently paused to accelerate the W80 LEP in support of the U.S. Air Force Long-Range Standoff missile.

Engineer Hank O'Brien, W78/88-1 LEP program manager, recounts that at the start of stockpile stewardship, scientists and engineers did not envision LEPs. "The focus of stockpile stewards was on building new experimental and computational resources and increasing our scientific knowledge," says O'Brien. "A few years later it became apparent we needed to perform work on the W87, and so we started thinking of life-extension programs." The W87 LEP took about 10 years to complete. The W78/88-1 LEP will take about 20 years from start to finish.

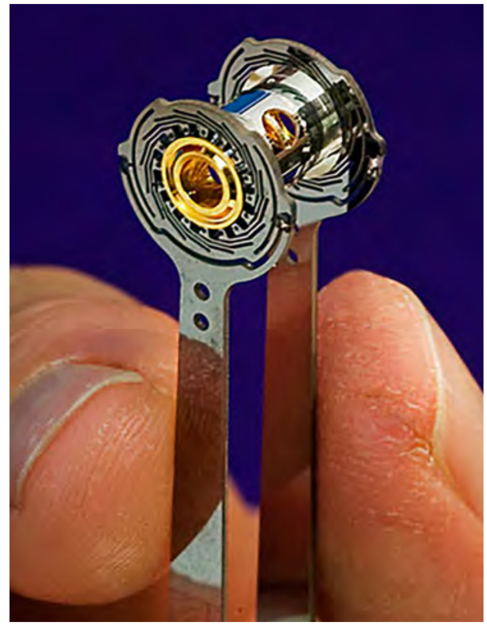
Weapons manufacturing processes are currently five decades old, and sustaining these legacy processes for producing LEP components is an increasing challenge. Many of the original materials and methods are no longer used because of environmental and health considerations. According to O'Brien, Livermore stockpile stewards search for ways to manufacture replacement components that are less expensive, more environmentally friendly, and simpler to certify. One promising new technique is additive manufacturing, in which materials such as a polymer or metal are added layer by layer to produce objects with complex shapes and desirable material properties. (See *S&TR*, January/February 2015, pp. 4–11.) "With additive manufacturing, we can design our own material," says O'Brien. "We can pick the density of a plastic cushion or dictate the stiffness of a metal."

Re-Creating the Sun's Temperatures

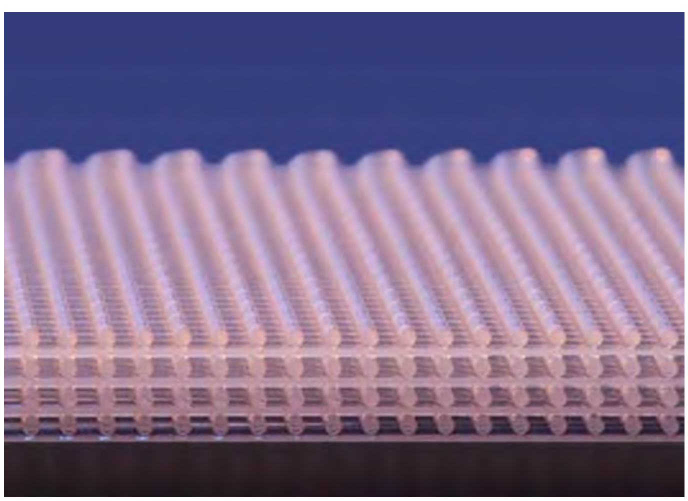
In the post-test era, scientists must rely on alternative methods for measuring the dynamic properties of weapons materials. The 192-beam NIF, the most energetic laser in the world, is stockpile stewardship's flagship facility for high-energy-density physics experiments. NIF is capable of reaching temperatures of 100 million degrees and pressures 100 billion times that of the Earth's atmosphere—conditions similar to those in stars and detonating nuclear weapons. Producing these extreme high-energy-density environments is critical to validating theoretical models and simulation codes that improve understanding of weapons physics.

NIF experiments have provided invaluable data about materials properties at regimes otherwise inaccessible in the absence of nuclear testing. Key material properties data include equation of state and material strength. "NIF has been phenomenally useful," says physicist Desmond Pilkington, program director for Weapon Physics and Design. During the past two years scientists have made significant progress toward realizing ignition and energy gain on NIF, which is relevant to understanding thermonuclear processes in weapons. Pilkington says, "Achieving ignition will move our research to the next energy phase, but it is not the only goal. NIF will continue to open up many more doors to scientific discovery for stockpile stewardship."

Equipped with approximately 70 optical, x-ray, and nuclear diagnostics, the giant laser also helps address questions regarding design options being considered in LEPs. Changes to weapons systems through LEPs can have unintended consequences. Together with computational models, NIF experiments provide valuable data for fully validating LEP concepts prior to implementation.



Experiments at the National Ignition Facility help scientists understand thermonuclear processes in weapons. A fully assembled ignition target incorporates a capsule assembly, hohlraum, and a surrounding thermal–mechanical package with silicon cooling "arms."



Life-extension programs necessitate the adoption of new manufacturing processes such as additive manufacturing. Livermore researchers produced a silicone cushion with programmable mechanical energy absorption properties through a three-dimensional printing process using a silicone-based ink.

Surrogate Testing with Computers

When stockpile stewardship was first formulated, scientists knew that unprecedented computational capabilities were needed to integrate the vast amount of scientific knowledge of nuclear weapons processes and materials and the accumulated experimental data from hundreds of nuclear tests. The Advanced Simulation and Computing (ASC) Program (formerly known as the Accelerated Strategic Computing Initiative, or ASCI) was launched to address this need. Dedicated to improving computational power by at least a millionfold, ASC quickly became one of the most significant accomplishments of stockpile stewardship. The program has also contributed to making high-performance computing an essential element of scientific research and spurred the U.S. high-performance computing industry.

ASC simulations offer a computational surrogate for nuclear testing by accurately modeling the extraordinary complexity of nuclear weapons systems. Major advances in hardware and software have made possible a clearer understanding of the issues involved in stockpile stewardship. Full 3D, high-fidelity simulations allow physicists to observe phenomena nanosecond by nanosecond, with a level of spatial resolution and a degree of physics realism previously unobtainable.

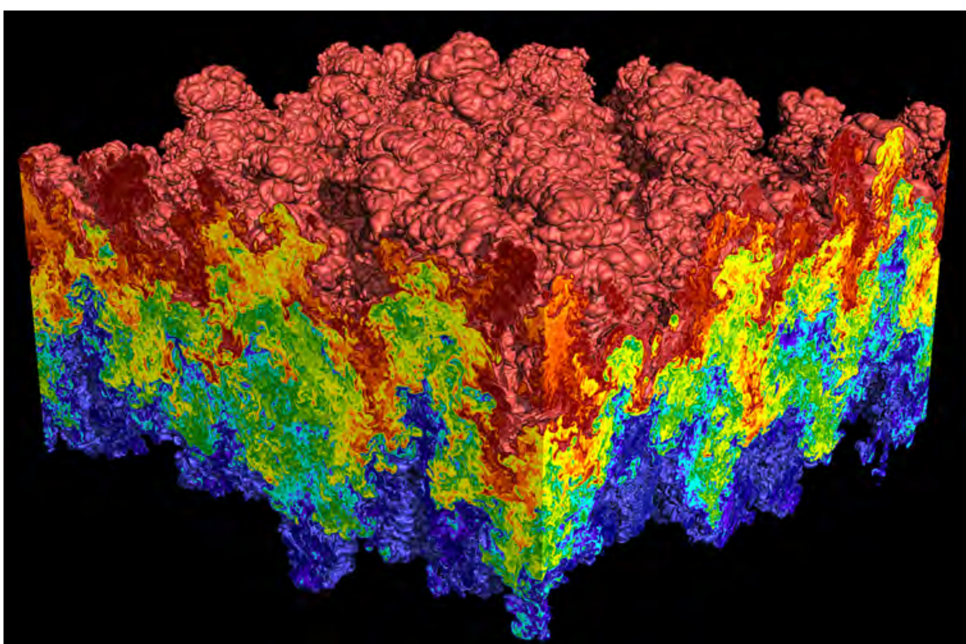
NNSA laboratories continue to house some of the world's fastest, most powerful supercomputers, including Livermore's 20-petaflop (quadrillion floating-point operations per second) Sequoia machine. "The calculations we run on Sequoia are incredibly involved," says Pilkington. "Often, we find the physics is more complex than we first assumed. To understand this complexity, particularly the interaction between all aspects of a nuclear weapon, we need a high-resolution, full-system model, which requires much larger calculations." Most full-system simulations are still in 2D. Graduating to 3D simulations will require more powerful supercomputers. Livermore scientists are preparing for the next-generation supercomputer, Sierra, which will provide four to six times Sequoia's sustained performance, with a peak performance speed of 120–150 petaflops.

A key accomplishment of Livermore's ASC-supported research has been the refining quantification of margins and uncertainties (QMU), an approach similar to engineering safety factors. This methodology brings together data from simulations, experiments, and theory to establish confidence factors for the key potential failure modes in weapons systems. For example, QMU helps weapons scientists rank the design options identified for LEPs.

Taking Better Care of Weapons

Mike Dunning, principal deputy for WCI, asserts that stockpile stewardship has been so successful because of the significant investments made over the past two decades in facilities, computing power, and technical expertise. However, he cautions that the Laboratory must maintain its expertise and guard against being overly confident as weapons continue to age and stockpile stewards are called upon to enhance weapons safety and security and package weapons on new platforms. "Experiments play an essential role in providing the data to develop, improve, and ultimately validate understanding of our models," says Dunning. "Equally important, experiments provide opportunities for our workforce to develop the judgment required to make the compromises inherent in taking a design from a computer model to something that can be engineered, built, assembled, and diagnosed. We really do and will continue to benefit from these capability investments."

Stockpile stewardship is a continuous process that requires the right tools for the job. "Nothing is wrong with the stockpile now, but we have a much smaller production complex than we used to if we need to make changes," says Verdon. "I'm pleased that the nation is making important investments in production facilities." He notes that a healthy complex is a crucial



Researchers used the Laboratory's BlueGene/L supercomputer to create (left) a high-resolution simulation of turbulent thermonuclear burning in a Type 1a supernova. (bottom) The Livermore Computing Complex houses most of the Laboratory's supercomputers. (Photograph by George A. Kitrinos.)

Finding a Balance

One of the most notable accomplishments of stockpile stewardship was a theoretical advance, namely, solving a mystery that had confounded some of the smartest physicists for five decades. Livermore physicist Omar Hurricane won the Department of Energy's prestigious E.O. Lawrence Award for leading a team that solved the mystery of missing energy produced during nuclear tests.

"The energy balance problem was first recognized in the 1960s when Livermore developed the first two-dimensional radiation hydrodynamic simulation tools. Over many decades when those tools were applied to conducted nuclear tests, it appeared that the tests violated a basic principle of physics known to every college freshman physics student: conservation of energy," says Hurricane. Many scientists had their own hypotheses about the missing energy, and all sorts of arguments raged, but the issue was never resolved. "It was something weapons designers needed to be aware of but didn't have time to address because they were fighting the Cold War," he says. "Back then, solving energy balance was less important because weapons designers could always conduct an underground nuclear test and see to what degree the principle was violated. The test data would then be folded into their codes. The entire Cold War was fought with that gap in understanding. The tests usually worked, but the issue still nagged at people because of the potential problems if you got the energy balance wrong."

When underground testing ended in 1992, solving the energy balance mystery became important because weapons designers could no longer rely on new test data to validate their codes. Starting in the early 2000s, Hurricane began leading a decade-long scientific effort to find the missing energy. "We got to the bottom of why we had a discrepancy between the results from our models and test results," he says. "Most of the components of the solution had been hypothesized previously by designers. However, a novel part crossed many disciplinary boundaries, which is why it evaded solution for so long."

Hurricane says that without the team's solution, scientists would be less certain whether changes made to the stockpile would affect the energy balance. "We are more confident executing life-extension programs and using new processes and materials. Stockpile stewardship would be much different today without this solution."

component of sustaining the nation's nuclear deterrent and provides a hedge against technological surprise.

Pilkington observes that the enduring stockpile "is a testament to the people who designed the weapons." One of the major concerns of stockpile stewardship architects was preserving the core intellectual and technical competencies of the weapons laboratories. As Pilkington notes, "People, not models, make decisions and certify LEPs."

Retaining the skills, knowledge, and abilities of stockpile stewards is paramount. "Weapons designers used to receive critical experience by performing underground tests," says Verdon. "Now, they are obtaining similar experience working on experiments at NIF, CFF, and other NNSA facilities. Physicists and engineers still have to work together and make judgments with incomplete information, just like they did during nuclear testing." He adds that Livermore people working on LEPs also gain valuable real-world experience by collaborating with NNSA production plants on LEP components.

Verdon also notes that the stockpile stewardship "methodology" has resulted in greater ability and confidence in computational design and testing. These advances have led to tighter design cycles for new conventional weapons systems such as the low-collateral-damage bomb called BLU-129/B. (See *S&TR,* March 2013, pp. 4–9.) He says, "We developed BLU-129B on a much shorter timescale than had ever been accomplished with previous munitions." A prototype was designed and virtually tested using advanced computational techniques. Computers then guided researchers to select the most stressing experiments to validate the design.

In the 20 years since it was established, the Stockpile Stewardship and Management Program has developed highly effective capabilities for maintaining confidence in the U.S. nuclear deterrent. In 2012, NNSA commemorated the 20th anniversary of the last U.S. nuclear explosives test and the success of the Stockpile Stewardship and Management Program, noting that the United States has no plans to conduct such tests in the future.

Stockpile stewardship is not without risk as weapons continue to age and national security requirements change. However, it has proven itself as the best approach to ensuring a safe, secure, and effective nuclear stockpile as long as nuclear weapons exist. "I believe we are taking better care of these weapons today than when we were conducting nuclear tests," says Goodwin. "We have developed a greater understanding of the way nuclear weapons work because we could not test them."

—Arnie Heller

Key Words: Advanced Simulation and Computing (ASC), Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS), Comprehensive Nuclear-Test-Ban Treaty (CTBT), Contained Firing Facility (CFF), Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility, Energetic Materials Center, energy balance, High Explosives Applications Facility (HEAF), Joint Actinide Shock Physics Experimental Research (JASPER) Facility, life-extension program (LEP), LLM-105, LX-21, National Ignition Facility (NIF), National Nuclear Security Administration (NNSA), Nevada National Security Site, plutonium-239, Sequoia, Sierra, Stockpile Stewardship and Management Program, U1A complex, W78/88-1.

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